Preface to Marine Geology Special Issue: *Geological Records of Extreme Wave Events*

1. Introduction

Extreme wave events, including tsunamis and storm surges, present major hazards to coastal communities around the world. In excess of 10 % of the global population lives in coastal areas at elevations below 10 m, including 21 % of the urban population of the Least Developed Countries (LDC) group, 50 nations with the most vulnerable economic statuses (McGranahan et al., 2007; Neumann et al., 2015). Geological investigations significantly enhance our understanding of tsunamis and storm surges, with field studies and modelling approaches contributing to improved knowledge of their long-term frequency-magnitude patterns. These long-term perspectives are required to adequately assess and model the hazards posed by future extreme wave events. The demand for geologically-supported coastal hazard assessments is continuously rising as anthropogenic sea-level rise accentuates the impact of extreme wave events (Kemp and Horton, 2013; Kron, 2013; Brown et al., 2014). As detailed geological examination of the deposits left by tsunamis and storm surges constitutes a relatively recent scientific endeavour (see Tappin (2017) for an overview of the development of tsunami geology research), recent years have seen a rapid expansion in the range of approaches employed (Nott, 2004; Shiki et al., 2008; Goff et al., 2012; Muller et al., 2017). Responding to the need for increased dialogue, collaboration and the exchange of ideas, a thematic session held at the European Geosciences Union (EGU) annual meeting in April 2016 and again in April 2017 brought together scientists from disparate strands of extreme wave event research. In total, 194 scientists have contributed 53 presentations to the first two gatherings of the *Geological Records of Extreme Wave Events* session. These contributions included case studies from recent, historic and prehistoric tsunami and storm surge events, covered coarse-clast and fine sediment records, ranged from low to high latitude regions and described both coastal and offshore records. Presentations have detailed the latest advances in identifying, characterising, dating and modelling evidence for extreme wave events. Based on these contributions, this special issue brings together 16 papers highlighting the latest developments in the field. Collectively, this issue includes a world-wide distribution of research (Fig. 1), with papers covering three broad themes: modern analogues, long-term records and modelling of extreme wave events.

1.1 Modern analogues of extreme wave events

Contemporary extreme wave events provide opportunities to characterise the sedimentary and geomorphic signatures of events of known source, magnitude and impact. These investigations may provide new understanding of event characteristics (e.g. Goto et al., 2011; Soria et al., 2016), highlight previously unstudied archives (e.g. Goni et al., 2007; Sakuna et al., 2012; Sawai et al., 2012) and both inspire and facilitate the development of novel methodologies (e.g. Wassmer et al., 2010; Chagué-Goff et al., 2012). Post-event surveys provide valuable field observations and datasets against which numerical models may be tested and refined (see section 1.3). Repeat surveys provide insights into the preservation potential of extreme wave event deposits and their incorporation into the geological record (Szczuciński, 2012; Spiske et al., 2013). In turn, studies of contemporary events act as modern analogues, enhancing the interpretation of older geological records of tsunamis and storm surges (see section 1.2).

Seven research papers in this special issue focus on sedimentary evidence for recent storms. Hong et al. (2017) report the findings of a rapid survey made three months after Tropical Cyclone Pam made landfall in Vanuatu in March 2015. The authors document flow heights of up to 5.29 m at an inundation distance of 106 m from the shoreline. Sedimentary evidence extends up to 320 m inland, with pumice layers found at greater distances from the shoreline than finer-grained sand sheets. Stemming from the same field survey, Kosciuch et al. (2017) focus on Tropical Cyclone Pam's microfossil signature. Investigating foraminiferal assemblages in the onshore sand sheets, the authors highlight the intertidal and shallow subtidal zones as the primary sediment sources.

Bregy et al. (2017) investigate sediment transport associated with hurricanes Camille and Katrina, which struck the Gulf of Mexico in 1969 and 2005 respectively. The authors use these modern analogues to identify storm surge deposits preserved in coastal marsh sediments in Mississippi, USA. The offshore origin of the prehistoric storm surge deposits and modelled flooding levels indicate similar storm surge magnitudes as during the two recent category 5 hurricanes.

Typhoon Haiyan made landfall in the Philippines in November 2013, with the interaction of wave sets and particular offshore bathymetry resulting in destructive long-period infragravity waves particularly around Hernani, eastern Samar (Roeber and Bricker, 2015). Soria et al. (2017) document both fine- and coarse-grained deposits associated with this event. A carbonate sand sheet extending >300 m inland contains foraminifera again indicative of shallow nearshore and beach environments. Seaward of this deposit, the storm surge also transported boulders, the majority ≤ 10 t, across a reef flat. The ability of storms to move boulders is also the focus of a study by Cox et al. (2017). Investigating sites in the Shetland Islands and western Ireland, the authors demonstrate an inverse correlation between quantitative boulder roundness measurements and boulder elevation in coastal locations. Their work not only highlights the utility of the Kirkbride device (Kirkbride, 2005) for deriving robust and repeatable roundness values but also marks an important step towards a much-needed sedimentological model of coastal boulder deposit emplacement.

Coastal sand ridge sequences may provide information on extreme wave frequency and magnitude. May et al. (2017) investigate the processes responsible for chenier-type ridge formation in Giralia Bay, Australia, a region with a documented history of both tropical cyclone and tsunami inundation. Their combination of monitoring from 2013 to 2015, a period including Tropical Cyclone Olwyn, stratigraphic analysis and dating highlights the importance of episodic events (both storm surges and extreme rainfall) in driving sand accretion and ridge development.

Pham et al. (2017) contrast the sedimentological characteristics of a fine-grained 2007 storm deposit and the 2004 Indian Ocean tsunami sand layer, in addition to two older tsunami deposits, encountered at a site on Phra Thong Island, Thailand. The authors demonstrate that discrimination between storm surge and tsunami deposits – a longstanding and ongoing debate within the community – is complex, with the Phra Thong deposits largely indistinguishable in their mineral content and trace element geochemistry. Three further papers in this issue document fine-grained sedimentary evidence for recent tsunamis. Tanigawa et al. (2017) focus on diatom assemblages in the 2011 Tōhoku tsunami deposits along the Misawa coast of Aomori Prefecture, northern Japan. The mixed assemblages of marine, brackish and freshwater species imply the deposit originates from a variety of sediment sources, including the coastal forest, intertidal zone and potentially also subtidal environments. Investigating the deposits left by the 2015 Illapel tsunami close to La Serena and Coquimbo, Chile, Bahlburg et al. (2017) detail a diverse array of sedimentary structures. Grain-size distributions suggest beach sands provided source materials, while water escape structures, rarely documented in extreme wave event deposits but abundant and wellpreserved here, are postulated as a mechanism for the homogenisation of some tsunami-deposited sand layers. Falvard et al. (2017) focus on a tsunami generated by a volcano, rather than a megathrust earthquake: the 1996 phreatomagmatic eruption in Karymskoye Lake on the Kamchatka Peninsula. The authors employ X-ray computed tomography to investigate heavy mineral distributions in the landward thinning and fining deposit, highlighting the significant potential of this technique.

1.2 Long-term records of extreme wave events

Geological investigations form an essential, yet still underutilised approach to capture crucial information on the frequency and magnitude of tsunamis and storm surges. Long-term records have provided important insights into the timing, magnitude and generation mechanisms of some of the largest tsunamis (MacInnes et al., 2010; Sawai et al., 2012; Sugawara et al., 2012) and storms (Toomey et al., 2013; Woodruff et al., 2015; Soria et al., 2016). Detailed sedimentological investigations, combined with high-resolution chronological approaches, have shed light on the lengths of and variability in past recurrence intervals (Cisternas et al., 2005; Donnelly and Woodruff, 2007; Yu et al., 2009; Atwater et al., 2017; Rubin et al., 2017). Such information is crucial for providing geological grounding for assessments of current and future coastal hazards.

Cisternas et al. (2017) detail evidence for eight episodes of tsunami inundation, at least seven of which are also associated with coincident seismic shaking, over the millennium leading up to the 1960 Chilean earthquake. Investigating sand layers and debris flow deposits on Isla Chiloé, south central Chile, the authors identify recurrence intervals averaging 85 years between some tsunamis, an interval only slightly longer than that which has passed since the most recent devastating tsunami in the region. Furthermore, their findings indicate significant variability in tsunamigenic earthquake magnitude.

Archaeological sections along Mediterranean shorelines contain evidence for tsunami and storm surge deposition, providing chronological control and cultural context to past extreme wave events. Hoffmann et al. (2017) examine an eroding coastal section from the ancient city of Ashkelon, Israel, and report stratigraphic evidence for either a tsunami or large storm. The deposit contains rip-up clasts, marine indicative foraminifera and broken diagnostic pottery, placing the timing of the event somewhere between 500 and 290 BC. The absence of this event in historical texts highlights the need for geological investigations in establishing long term records of extreme wave events.

Shallow subtidal regions have only recently received attention as extreme wave event depocentres, despite recognition that the absence of significant anthropogenic alteration may increase the preservation potential of these settings. Investigating the shelf off Jisr al-Zarka, Israel, Tyuleneva et al. (2017) report stratigraphic evidence for at least four potential tsunami deposits from a water depth of 15 m. The oldest event, dated to ~6000 to 5600 cal a BP, lengthens the known palaeotsunami history of this region and the study adds to a growing body of work developing approaches to investigate these offshore settings.

Long sedimentary records can similarly extend the record of storm surge occurrence significantly beyond the instrumental and historical record. Bregy et al. (2017) present a 2500-year record of hurricane-driven storm surges from a former coastal marsh in Mississippi, USA. The authors identify 1900 – 900 cal a BP as a period of quiescence, and 900 to 600 and 2200 to 1900 cal a BP as periods with particularly frequent hurricanes, contributing to the understanding of temporal and geographical hurricane variability in the Northern Gulf of Mexico.

While Cox et al. (2017) are able to determine that boulders in the Shetland Islands and Western Ireland have been moved multiple times based on quantitative roundness estimates, ascertaining the absolute timing of boulder transport remains a persistent difficulty for many coarse-clast investigations. Addressing this issue on the reef platforms of Bonaire, Rixhon et al. (2017) investigate the utility of three different dating approaches: radiocarbon dating of boring bivalves, $^{230}Th/U$ dating of post-depositional features and ^{36}Cl surface exposure dating. The latter two approaches have not previously been applied in studies of extreme wave events, but show considerable potential for dating boulder transport by tsunamis and potentially also storm surges.

1.3 Modelling extreme waves

Modelling approaches offer the possibility of inferring and quantifying the characteristics of extreme waves based on their sedimentary or geomorphic evidence (Jaffe and Gelfenbaum, 2007; Moore et al., 2007; Woodruff et al., 2008). Modelling of recent extreme waves with known magnitudes and inundation characteristics provides understanding of the relationship between these events and their consequential deposits. This understanding can then be applied to older extreme wave event deposits to provide greater insight into past event magnitudes and impacts. The presence or absence of extreme wave deposits, their lateral and vertical extent and their grain-size distributions may be used to test and refine forward models. Increasingly, inverse models are used to derive flow speeds, depths and inundation distances from the same field data. These quantitative estimates are of great importance for a range of future resilience and mitigation approaches, from the siting of evacuation centres to the design of wave-resistant structures. Five papers in this issue are united by their use of numerical modelling to understand and assess extreme wave characteristics.

Noting the similarity of the bore-like Typhoon Haiyan storm surge to tsunami flooding, Soria et al. (2017) apply the TSUFLIND inverse model (Tang and Weiss, 2015) to investigate flow speeds. The model, developed for and tested on tsunami deposits, is applied here for the first time on a storm deposit. In their contribution, Tang et al. (2017) report an enhanced version of the TSUFLIND model. Using an established record of grain size distributions in the 2004 Indian Ocean Tsunami deposit at Ranganathapuram, India (Bahlburg and Weiss, 2007), alongside a hypothetical idealized tsunami deposit, the authors develop the TSUFLIND-EnKF model to derive flow speed and depth from deposit thicknesses and grain-size distributions. The inclusion of Ensemble Kalman Filtering quantifies uncertainties in the inversion results, providing final results as probability density distribution functions rather than simply individual values or ranges.

Hong et al. (2017) and Bregy et al. (2017) also adopt inverse approaches, both using the Woodruff et al. (2008) sediment transport model to estimate storm surge flow depth from grain-size distributions. Looking at Tropical Cyclone Pam (Hong et al., 2017) and Hurricanes Katrina and Camille (Bregy et al., 2017), both studies achieve a good level of fit between flow depths derived from the inverse model and other independently obtained direct measurements. Bregy et al. (2017) also apply the model to pre-instrumental storm surge deposits, inferring flow depths of up to 7.1 m, but noting the possibility of underestimating the highest events.

Continuous coastal vegetation has long been considered as providing protection for coastal areas from extreme wave events. Discontinuous vegetation has not received the same focus; addressing this, Zainali et al. (2017) adopt a numerical approach to investigate the interaction between a solitary wave and patchy vegetation. Using Serre-Green-Naghdi equations and validating their results with numerical and physical modelling results from previous studies, the authors find that vegetation patches reduce the maximum wave momentum, but may increase local water depths.

2. Expanding the proxy tool-kit

The papers in this special issue highlight the broad range of approaches currently being used to analyse sedimentary and geomorphic signatures of extreme wave events. Collectively, these methods are termed the 'proxy tool-kit', a phrase initially applied in the context of palaeotsunami research (Chague-Goff et al., 2011; Goff et al., 2012), but also appropriate to embody approaches used to investigate geological records of storm surges. Each of the primarily field-based studies documented in this issue utilises more than one of the 'tools', highlighting the importance of multi-proxy approaches. The range of different methods furthermore underlines that there is no single blanket approach that can be applied to all environments; rather the proxy tool-kit must be selected from and adapted to the particular context and local environment of each study.

Stratigraphic and sedimentological analyses are widely applied by papers in this issue (Bahlburg et al., 2017; Bregy et al., 2017; Cisternas et al., 2017; Falvard et al., 2017; Hoffmann et al., 2017; Hong et al., 2017; Kosciuch et al., 2017; May et al., 2017; Pham et al., 2017; Soria et al., 2017; Tanigawa et al. 2017; Tyuleneva et al. 2017). Supplementing visual sediment descriptions, grain-size analysis provides a key indicator of sediment transport and deposition and is used by the majority of papers listed above. While most studies use laser diffraction, Falvard et al. (2017) derive grain-size distributions and additional qualitative sedimentological inferences from X-ray CT images. Where appropriate sources of coarse clasts exist, extreme wave events have the potential to move boulders. Cox et al. (2017) and Soria et al. (2017) discuss coarse-clast distribution and size, with the former contribution also deriving quantitative clast roundness estimates.

Bregy et al. (2017) and Soria et al. (2017) use organic content derived by loss-on-ignition to differentiate between extreme wave event deposits and background sediments and to investigate spatial trends in recent deposits. May et al. (2017) document variations in total carbon, total organic carbon and total nitrogen. Mineral assemblages, including heavy minerals, may provide information on sediment sources and flow dynamics (Falvard et al. 2017; Pham et al., 2017; Tyuleneva et al., 2017). Trace element geochemistry may also attest to sediment origins (May et al., 2017; Pham et al., 2017; Tyuleneva et al., 2017), though issues over post-depositional alteration remain.

Taxonomic and taphonomic analyses of easily-transported microfossil groups inform investigations into the provenance of extreme wave deposits (Pilarczyk et al., 2014; Dura et al., 2016). Hoffmann et al. (2017), Kosciuch et al. (2017) and Soria et al. (2017) employ quantitative counts of foraminifera, Cisternas et al. (2017) and Tanigawa et al. (2017) focus on diatoms, while Bregy et al. (2017) look at both groups.

A multi-proxy approach is also beneficial for determining chronologies of tsunami and storm surge deposits in many settings. While radiocarbon dating is typically the method of choice for fine-grained deposits in terrestrial environments (Cisternas et al., 2017) and offshore settings (Tyuleneva et al., 2017), Bregy et al. (2017) supplement this approach with ^{137}Cs dating for the most recent events. The many problems associated with dating coarse-clast records particularly benefit from a combination of approaches, e.g. by dating both the transport event and post-depositional features (Rixhon et al., 2017).

3. Recommendations for future research

Collectively, the papers in this special issue exemplify the current state of extreme wave event research. Discussions at the *Geological Records of Extreme Wave Events* sessions at the European Geosciences Union annual meetings, along with the papers presented here, have highlighted a number of continuing and emerging topics and debates within the community. These range from the perennial difficulty in differentiating storm surge and tsunami deposits to the development of new proxy records and chronological approaches. We hope that this special issue helps to focus future research in a number of areas. Studies of recent storm surge and tsunami events (e.g. Bahlburg et al., 2017; Bregy et al., 2017; Cox et al., 2017; Pham et al., 2017; Falvard et al., 2017; Hong et al., 2017; Kosciuch et al., 2017; May et al., 2017; Soria et al., 2017; Tanigawa et al., 2017) are critical for advancing understanding of long-term records. To enable greater application of these modern analogues, further study of thresholds of evidence creation and preservation (including post-depositional alteration) is required.

The difficulties in distinguishing between tsunami and storm surges based on their geological imprints are widely appreciated (e.g. Shanmugam, 2012; Costa et al., 2015). In this issue, Pham et al. (2017) highlight issues over discriminating extreme wave events in Thailand, while Hoffmann et al. (2017) and Tyuleneva et al. (2017) discuss difficulties in relation to deposits in the Mediterranean. We suggest that, in certain circumstances, additional lines of corroborating evidence may favour one interpretation over the other. For example, overwash deposition coincident with abrupt land-level change may suggest a tsunami accompanied by coseismic deformation (Hemphill-Haley, 1995; Dura et al., 2016). For recent extreme wave events, high-precision dating may facilitate cross-correlation with historical storm and tsunami records (Araoka et al., 2010; Atwater et al., 2015). Nevertheless, in many instances, such supporting evidence is not available. In these situations, detailed multi-proxy analyses combined with comprehensive assessments of site specific characteristics and supplemented with modelling approaches currently offer the most promising way forward.

Long records of storm surge and tsunami occurrence provide important long-term perspectives on coastal hazards, but continued and deepened collaboration between field scientists and modellers is required to extract the most from these records. Future dialogue should focus on how field observations can be tailored to enhance modelling approaches and, conversely, how modelling may guide field studies.

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Figures:

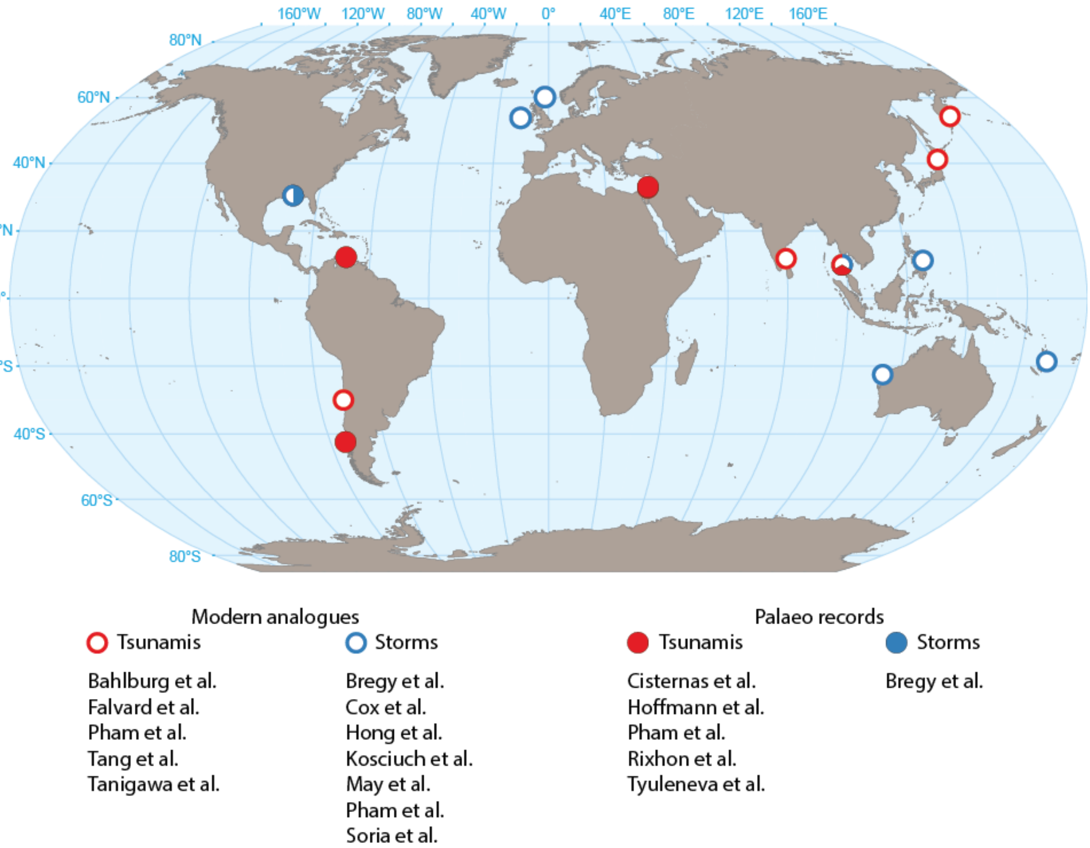

Figure 1: Field locations of the extreme wave event studies reported in this special issue.